



TITLE:

# On Asymptotic Solutions of Nonlinear and Linear Abel-Volterra Integral Equations

AUTHOR(S):

Kilbas, Anatoly A.; Saigo, Megumi

---

CITATION:

Kilbas, Anatoly A. ...[et al]. On Asymptotic Solutions of Nonlinear and Linear Abel-Volterra Integral Equations. 数理解析研究所講究録 1994, 881: 91-111

ISSUE DATE:

1994-08

URL:

<http://hdl.handle.net/2433/84221>

RIGHT:

# On Asymptotic Solutions of Nonlinear and Linear Abel-Volterra Integral Equations

Anatoly A. Kilbas\* (ベラルーシ国立大学)

Megumi Saigo† [西郷 恵] (福岡大学理学部)

## Abstract

The paper is devoted to consider nonlinear Abel-Volterra integral equations of the form

$$\varphi^m(x) = \frac{a(x)}{\Gamma(\alpha)} \int_0^x \frac{\varphi(t)dt}{(x-t)^{1-\alpha}} + f(x) \quad (0 < x < d \leq \infty)$$

with  $\alpha > 0, m \neq 0, -1, -2, \dots$ , which includes the linear case for  $m = 1$ . The asymptotic behavior of the solution  $\varphi(x)$ , as  $x \rightarrow 0$ , is obtained, provided that  $a(x)$  and  $f(x)$  have the special asymptotic behavior near zero.

## 1. Introduction

The nonlinear Volterra convolution integral equation

$$\varphi^m(x) = \int_0^x k(x-t)\varphi(t)dt + f(x) \quad (x > 0) \quad (1.1)$$

with  $m > 1$  and more general non-convolution equation

$$\varphi^m(x) = a(x) \int_0^x k(x-t)\varphi(t)dt + f(x) \quad (x > 0) \quad (1.2)$$

with  $m > 1$  were studied in [1], [4], [6], [14], [17]-[19] and [2], [3], [5], [7], respectively. The interest to these equations is caused by their applications in nonlinear theory of water perlocation [8], [19]. The above papers were devoted to investigate existence, uniqueness and stability of the nontrivial solution  $\varphi(x)$  and the method of successive approximation to the homogeneous and nonhomogeneous equations (1.1) and (1.2). In particular, if  $k(u) = u^{\alpha-1}$  ( $\alpha > 0$ ) the equations (1.1) and (1.2) are Abel's type integral equations which have

\*Department of Mathematics and Mechanics, Byelorussian State University, Minsk 220080, Belarus

†Department of Applied Mathematics, Fukuoka University, Fukuoka 814-80, Japan

applications in nonlinear theory of wave propagation [15], [22] (see [10] and [21] for the theory and other applications of Abel's type integral equations).

The problem to find solutions of the equations (1.1) and (1.2) in closed forms or their asymptotic solutions near zero and infinity, provided that such a solution exists, is also of importance. The solution in closed form of the homogeneous Abel-Volterra integral equation

$$\varphi^m(x) = \frac{a}{\Gamma(\alpha)} \int_0^x \frac{\varphi(t) dt}{(x-t)^{1-\alpha}} \quad (x > 0) \quad (1.3)$$

with  $\alpha > 0, a \in \mathbf{R}$  was obtained for  $m > 1$  in [22] (see also [1] and [4]), where  $\mathbf{R}$  is meant the real number field. The asymptotic behavior, of the solution  $\varphi(x)$  as  $x \rightarrow 0$  and  $x \rightarrow \infty$  of the Abel-Volterra integral equation of the form

$$\varphi(x) = \frac{1}{\Gamma(\alpha)} \int_0^x \frac{f(t) - [\varphi(t)]^m dt}{(x-t)^{1-\alpha}} + f(x) \quad (x > 0) \quad (1.4)$$

with  $\alpha > 0$  and  $m > 1$  in the cases when  $f(x)$  has the general power asymptotics near zero and infinity was studied in [13] and [20] for  $\alpha = 1/2$  and in [9] for any  $\alpha > 0$  (see also [11] in this connection), and several first terms of asymptotics of  $\varphi(x)$  were obtained. It should be noted that the asymptotic behavior of solutions of nonlinear Volterra equations more general than (1.2) was considered by many authors (see the results and bibliography in the book [5; Chapters 15, 17-20]), but most of the results are given only the first asymptotic term of the solutions.

Our paper deals with the investigation of the asymptotic behavior of a solution  $\varphi(x)$ , as  $x \rightarrow 0$ , of the Abel-Volterra equations of the form (1.2)

$$\varphi^m(x) = \frac{a(x)}{\Gamma(\alpha)} \int_0^x \frac{\varphi(t) dt}{(x-t)^{1-\alpha}} + f(x) \quad (0 < x < d \leq \infty) \quad (1.5)$$

with  $\alpha > 0, m \neq 0, -1, -2, \dots$ , provided that  $a(x)$  and  $f(x)$  have the asymptotics,

$$a(x) \sim x^{\alpha p m} \sum_{k=-l}^{\infty} a_k x^{\alpha k} \quad (x \rightarrow 0) \quad (1.6)$$

with  $a_{-l} \neq 0$  and

$$f(x) \sim x^{\alpha p m} \sum_{k=-n}^{\infty} f_k x^{\alpha k} \quad (x \rightarrow 0) \quad (1.7)$$

with  $f_{-n} \neq 0$ , respectively, where  $p = -1, 0, 1, \dots, l, n \in \mathbf{Z}$  being the set of integers. We show that under certain assumptions on parameters  $m, p, l$  and  $n$  the solution  $\varphi(x)$  of the equation (1.5) has the asymptotic expansion

$$\varphi(x) \sim \sum_{k=s}^{\infty} \varphi_k x^{\alpha k} \quad (x \rightarrow 0) \quad (1.8)$$

with  $s \geq -1$ , where the coefficients  $\varphi_k$  are expressed via  $a_k$  and  $f_k$ .

It should be noted that our method allows us to find the asymptotic solution, as  $x \rightarrow 0$ , of the linear Abel-Volterra integral equation

$$\varphi(x) = \frac{a(x)}{\Gamma(\alpha)} \int_0^x \frac{\varphi(t)dt}{(x-t)^{1-\alpha}} + f(x) \quad (0 < x < d \leq \infty) \quad (1.9)$$

with  $\alpha > 0$ , provided that  $a(x)$  and  $f(x)$  have the asymptotics (1.6) and (1.7) with  $m = 1$ . Such an asymptotic solution in the particular cases  $p = 0$ ,  $l = 1$  and  $n = 0, 1$  was obtained by authors in [16].

In Section 2 we prove two lemmas on an asymptotic representation of power of a function being given asymptotics. Sections 3 - 5 deal with the asymptotic solutions of the equations (1.5). Section 6 is devoted to the nonlinear equation (1.5) with the integer  $m = 2, 3, \dots$ . In section 7 we give asymptotic solutions of the linear equations (1.9).

## 2. Preliminaries

First we formulate the preliminary assertion.

**Lemma 1.** *Let  $p \in \mathbb{Z}$ ,  $\alpha \in \mathbb{R}$  and  $\{\varphi_k\}_{k=p}^{\infty}$  be a sequence of real numbers. If  $m$  is a real number such that  $m \neq 1, 0, -1, -2, \dots$  and*

$$\varphi(x) \sim \sum_{k=p}^{\infty} \varphi_k x^{\alpha k} \quad (x \rightarrow 0), \quad (2.1)$$

then

$$\varphi^m(x) \sim x^{\alpha pm} \sum_{k=0}^{\infty} \Phi_{p,k} x^{\alpha k} \quad (x \rightarrow 0), \quad (2.2)$$

where the coefficients  $\Phi_{p,k}$  are expressed via the coefficients  $\varphi_k$ :

$$\begin{aligned} \Phi_{p,0} &= \binom{m}{0} \varphi_p^m; \\ \Phi_{p,1} &= \binom{m}{1} \varphi_p^{m-1} \varphi_{p+1}; \\ \Phi_{p,2} &= \binom{m}{1} \varphi_p^{m-1} \varphi_{p+2} + \binom{m}{2} \varphi_p^{m-2} \varphi_{p+1}^2; \\ \Phi_{p,3} &= \binom{m}{1} \varphi_p^{m-1} \varphi_{p+3} + \binom{m}{2} \binom{2}{1} \varphi_p^{m-2} \varphi_{p+1} \varphi_{p+2} + \binom{m}{3} \varphi_p^{m-3} \varphi_{p+1}^3; \\ \Phi_{p,4} &= \binom{m}{1} \varphi_p^{m-1} \varphi_{p+4} + \binom{m}{2} \varphi_p^{m-2} \left[ \varphi_{p+2}^2 + \binom{2}{1} \varphi_{p+1} \varphi_{p+3} \right]; \\ &\quad + \binom{m}{3} \binom{3}{1} \varphi_p^{m-3} \varphi_{p+1}^2 \varphi_{p+2} + \binom{m}{4} \varphi_p^{m-4} \varphi_{p+1}^4; \end{aligned}$$

$$\begin{aligned}
\Phi_{p,5} = & \binom{m}{1} \varphi_p^{m-1} \varphi_{p+5} + \binom{m}{2} \binom{2}{1} \varphi_p^{m-2} [\varphi_{p+1} \varphi_{p+4} + \varphi_{p+2} \varphi_{p+3}] \\
& + \binom{m}{3} \varphi_p^{m-3} \left[ \binom{3}{1} \varphi_{p+1}^2 \varphi_{p+3} + \binom{3}{2} \varphi_{p+1} \varphi_{p+2}^2 \right] \\
& + \binom{m}{4} \binom{4}{1} \varphi_p^{m-4} \varphi_{p+1}^3 \varphi_{p+2} + \binom{m}{5} \varphi_p^{m-5} \varphi_{p+1}^5, \quad \text{etc.} \quad (2.3)
\end{aligned}$$

**Proof.** Using properties of asymptotic expansions [21, Section 16] we have, as  $x \rightarrow 0$ ,

$$\begin{aligned}
\varphi^m(x) & \sim x^{\alpha p m} \left( \sum_{k=0}^{\infty} \varphi_{k+p} x^{\alpha k} \right)^m \sim x^{\alpha p m} \sum_{j=0}^{\infty} \binom{m}{j} \varphi_p^{m-j} \left( \sum_{k=1}^{\infty} \varphi_{k+p} x^{\alpha k} \right)^j \\
& \sim x^{\alpha p m} \left\{ \binom{m}{0} \varphi_p^m + \binom{m}{1} \varphi_p^{m-1} \left[ \varphi_{p+1} + \sum_{k=1}^{\infty} \varphi_{k+p+1} x^{\alpha k} \right] x^{\alpha} \right. \\
& \quad \left. + \sum_{j=2}^{\infty} \binom{m}{j} \varphi_p^{m-j} x^{\alpha j} \left( \sum_{k=0}^{\infty} \varphi_{k+p+1} x^{\alpha k} \right)^j \right\} \\
& \sim x^{\alpha p m} \left\{ \binom{m}{0} \varphi_p^m + \binom{m}{1} \varphi_p^{m-1} \varphi_{p+1} x^{\alpha} \right. \\
& \quad + \left[ \binom{m}{1} \varphi_p^{m-1} \varphi_{p+2} + \binom{m}{2} \varphi_p^{m-2} \varphi_{p+1}^2 \right] x^{2\alpha} \\
& \quad + \binom{m}{1} \varphi_p^{m-1} x^{2\alpha} \sum_{k=2}^{\infty} \varphi_{k+p+1} x^{\alpha k} \\
& \quad + \binom{m}{2} \varphi_p^{m-2} x^{2\alpha} \left[ \binom{2}{1} \varphi_{p+1} \left( \sum_{k=1}^{\infty} \varphi_{k+p+1} x^{\alpha k} \right) + \left( \sum_{k=1}^{\infty} \varphi_{k+p+1} x^{\alpha k} \right)^2 \right] \\
& \quad \left. + \sum_{j=3}^{\infty} \binom{m}{j} \varphi_p^{m-j} x^{\alpha j} \left( \sum_{k=0}^{\infty} \varphi_{k+p+1} x^{\alpha k} \right)^j \right\}.
\end{aligned}$$

Continuing this process we obtain (2.5) - (2.6).

If  $m$  is an integer, then (2.2) can be written in another form.

**Lemma 2.** Let  $p \in \mathbf{Z}$ ,  $\alpha \in \mathbf{R}$  and  $\{\varphi_k\}_{k=p}^{\infty}$  be a sequence of real numbers. If  $m = 2, 3, \dots$  and the asymptotic expansion (2.1) holds, then, as  $x \rightarrow 0$ ,

$$\varphi^m(x) \sim x^{\alpha p m} \sum_{r=0}^{\infty} \Phi_{p,k} x^{\alpha k}, \quad (2.4)$$

$$\Phi_{p,0} = \varphi_p^m, \quad \Phi_{p,k} = \sum_{i_0=0}^{m-1} \sum_{i_1, i_2, \dots, i_j} \frac{m!}{i_0! i_1! i_2! \dots i_j!} \varphi_p^{i_0} \varphi_{p+1}^{i_1} \varphi_{p+2}^{i_2} \dots \varphi_{p+j}^{i_j}, \quad (2.5)$$

where the summation is taken over all nonnegative integers  $i_1, i_2, \dots, i_j$  such that

$$0 \leq i_1 \leq i_2 \leq \dots \leq i_j \leq k, \quad i_0 + i_1 + \dots + i_j = m, \quad i_1 + 2i_2 + \dots + ji_j = k. \quad (2.6)$$

### 3. Asymptotic Solutions of Nonlinear Equations in the Space of Locally Integrable Functions

In this section we obtain the asymptotic behavior of the solution  $\varphi(x)$  of the equation as  $x \rightarrow 0$

$$\varphi^m(x) = \frac{a(x)}{\Gamma(\alpha)} \int_0^x \frac{\varphi(t)dt}{(x-t)^{1-\alpha}} + f(x) \quad (0 < x < d \leq \infty) \quad (3.1)$$

for  $0 < \alpha < 1, m \in \mathbf{R}, m \neq 0, -1, -2, \dots$ , provided that  $a(x)$  and  $f(x)$  have the asymptotics

$$a(x) \sim x^{-\alpha m} \sum_{k=-l}^{\infty} a_k x^{\alpha k} \quad (x \rightarrow 0) \quad (3.2)$$

with  $l \in \mathbf{Z}, a_{-l} \neq 0$ , and

$$f(x) \sim x^{-\alpha m} \sum_{k=-n}^{\infty} f_k x^{\alpha k} \quad (x \rightarrow 0) \quad (3.3)$$

with  $n \in \mathbf{Z}, f_{-n} \neq 0$ .

First we consider the equation (3.1), where  $a(x)$  and  $f(x)$  have the asymptotics (3.2) and (3.3) in the case  $l = n \geq 0$ . We shall seek an asymptotic solution  $\varphi(x)$  of (3.1) in the form

$$\varphi(x) \sim \sum_{k=-1}^{\infty} \varphi_k x^{\alpha k} \quad (x \rightarrow 0). \quad (3.4)$$

Then, by Lemma 1

$$\varphi^m(x) \sim x^{-\alpha m} \sum_{k=0}^{\infty} \Phi_{-1,k} x^{\alpha k} \quad (x \rightarrow 0), \quad (3.5)$$

where the coefficients  $\Phi_{-1,k}$  are expressed via  $\varphi_k$  by (2.2) - (2.3) (with  $p = -1$ ). Applying (3.4) and Theorem 16.1 of [21], we have, as  $x \rightarrow 0$ ,

$$\frac{1}{\Gamma(\alpha)} \int_0^x \frac{\varphi(t)dt}{(x-t)^{1-\alpha}} \sim \sum_{k=-1}^{\infty} \frac{\Gamma(\alpha k + 1) \varphi_k}{\Gamma(\alpha k + \alpha + 1)} x^{\alpha k + \alpha}. \quad (3.6)$$

Using (3.2) and properties of asymptotic expansions, we obtain, as  $x \rightarrow 0$ ,

$$\begin{aligned} \frac{a(x)}{\Gamma(\alpha)} \int_0^x \frac{\varphi(t)dt}{(x-t)^{1-\alpha}} &\sim \sum_{k=0}^{\infty} \left( \sum_{i=0}^k \frac{a_{k-n-i} \Gamma(\alpha i - \alpha + 1) \varphi_{i-1}}{\Gamma(\alpha i + 1)} \right) x^{\alpha(k-n-m)} \\ &\sim x^{-\alpha m} \sum_{k=-n}^{\infty} \left( \sum_{i=0}^{k+n} \frac{a_{k-i} \Gamma(\alpha i - \alpha + 1) \varphi_{i-1}}{\Gamma(\alpha i + 1)} \right) x^{\alpha k}. \end{aligned} \quad (3.7)$$

From here, taking (3.1), (3.3) and (3.5) into account, we arrive at the following asymptotic relation, as  $x \rightarrow 0$ ,

$$x^{-\alpha m} \sum_{k=0}^{\infty} \Phi_{-1,k} x^{\alpha k} \sim x^{-\alpha m} \sum_{k=-n}^{\infty} \left( \sum_{i=0}^{k+n} \frac{a_{k-i} \Gamma(\alpha i - \alpha + 1) \varphi_{i-1}}{\Gamma(\alpha i + 1)} \right) x^{\alpha k} + x^{-\alpha m} \sum_{k=-n}^{\infty} f_k x^{\alpha k}, \quad (3.8)$$

where  $\Phi_{-1,k}$  are expressed via the coefficients  $\varphi_k$  by (2.2) and (2.3).

If  $n \geq 1$ , then we obtain from (3.8) that if the coefficients  $\varphi_k$  satisfy the relations

$$\sum_{i=0}^{k+n} \frac{a_{k-i} \Gamma(\alpha i - \alpha + 1) \varphi_{i-1}}{\Gamma(\alpha i + 1)} + f_k = 0 \quad (k = -n, -n+1, \dots, -1) \quad (3.9)$$

$$\Phi_{-1,k} = \sum_{i=0}^{k+n} \frac{a_{k-i} \Gamma(\alpha i - \alpha + 1) \varphi_{i-1}}{\Gamma(\alpha i + 1)} + f_k \quad (k = 0, 1, 2, \dots), \quad (3.10)$$

then (3.4) is the asymptotic solution of the equation (3.1). If  $n = 0$ , then it follows from (3.8) that if the coefficients  $\varphi_k$  satisfy the relations

$$\Phi_{-1,k} = \sum_{i=0}^k \frac{a_{k-i} \Gamma(\alpha i - \alpha + 1) \varphi_{i-1}}{\Gamma(\alpha i + 1)} + f_k \quad (k = 0, 1, 2, \dots), \quad (3.11)$$

then (3.4) is also the asymptotic solution of the equation (3.1).

From here we obtain the following result.

**Theorem 1.** Let  $n = 0, 1, 2, \dots$  and let functions  $a(x)$  and  $f(x)$  have asymptotic expansions

$$a(x) \sim x^{-\alpha n} \sum_{k=-n}^{\infty} a_k x^{\alpha k} \quad (x \rightarrow 0) \quad (3.12)$$

with  $0 < \alpha < 1$ ,  $a_{-n} \neq 0$  and (3.3). Let the coefficients  $\varphi_k$  satisfy the relations (3.9) and (3.10) if  $n > 0$  and the relation (3.11) if  $n = 0$ . Then the integral equation (3.1) is asymptotically solvable in the space of locally integrable functions on  $(0, d)$  with  $0 < d \leq \infty$ , and its asymptotic solution  $\varphi(x)$  has the form (3.4).

Now we consider the case  $n < l$  in the asymptotics of (3.2) and (3.3). We shall seek the asymptotic solution  $\varphi(x)$  of (3.1) in the form

$$\varphi(x) \sim \sum_{k=l-n-1}^{\infty} \varphi_k x^{\alpha k} \quad (x \rightarrow 0) \quad (3.13)$$

and come to the asymptotic relation

$$\begin{aligned} x^{\alpha(l-n-1)m} \sum_{k=0}^{\infty} \Phi_{l-n-1,k} x^{\alpha k} &\sim x^{-\alpha m} \sum_{k=-n}^{\infty} \left( \sum_{i=l-n}^{k+l} \frac{a_{k-i} \Gamma(\alpha i - \alpha + 1) \varphi_{i-1}}{\Gamma(\alpha i + 1)} \right) x^{\alpha k} \\ &+ x^{-\alpha m} \sum_{k=-n}^{\infty} f_k x^{\alpha k} \quad (x \rightarrow 0), \end{aligned} \quad (3.14)$$

where  $\Phi_{l-n-1,k}$  are expressed via the coefficients  $\varphi_k$  by (2.2) and (2.3).

Let now suppose that  $q = (l-n)m$  be an integer for  $m \neq 0, -1, -2, \dots$  such that  $q \geq -n$ . Then (3.14) is equivalent to the relation

$$x^{-\alpha m} \sum_{k=q}^{\infty} \Phi_{l-n-1,k-q} x^{\alpha k} \sim x^{-\alpha m} \sum_{k=-n}^{\infty} \left( \sum_{i=l-n}^{k+l} \frac{a_{k-i} \Gamma(\alpha i - \alpha + 1) \varphi_{i-1}}{\Gamma(\alpha i + 1)} \right) x^{\alpha k} + x^{-\alpha m} \sum_{k=-n}^{\infty} f_k x^{\alpha k} \quad (x \rightarrow 0). \quad (3.15)$$

From here we obtain that if  $q > -n$  and the coefficients  $\varphi_k$  satisfy the equalities

$$\sum_{i=l-n}^{k+l} \frac{a_{k-i} \Gamma(\alpha i - \alpha + 1) \varphi_{i-1}}{\Gamma(\alpha i + 1)} + f_k = 0 \quad (k = -n, -n+1, \dots, q-1), \quad (3.16)$$

$$\Phi_{l-n-1,k-q} = \sum_{i=l-n}^{k+l} \frac{a_{k-i} \Gamma(\alpha i - \alpha + 1) \varphi_{i-1}}{\Gamma(\alpha i + 1)} + f_k \quad (k = q, q+1, \dots), \quad (3.17)$$

then (3.13) is the asymptotic solution of the equation (3.1). If  $q = -n$ , then it follows from (3.15) that if the coefficients  $\varphi_k$  satisfy the relation (3.17), then (3.13) is also the asymptotic solution of the equation (3.1).

Thus we arrive at the following statement.

**Theorem 2.** Let  $l, n$  be integers with  $l > n$ ,  $q = (l-n)m$  be an integer for  $m \neq 0, -1, -2, \dots$  such that  $q \geq -n$ , and let the functions  $a(x)$  and  $f(x)$  have the asymptotic expansions (3.2) and (3.3). Let the coefficients  $\varphi_k$  satisfy the relations (3.16) and (3.17) when  $q > -n$  and the relation (3.17) when  $q = -n$ . Then the integral equation (3.1) is asymptotically solvable in the space of locally bounded functions on  $(0, d)$  with  $0 < d \leq \infty$ , and its asymptotic solution  $\varphi(x)$  has the form (3.13).

#### 4. Asymptotic Solutions of Nonlinear Equations in the Space of Locally Bounded Functions

In this section we obtain the asymptotic behavior, as  $x \rightarrow 0$ , of the solution  $\varphi(x)$  of the equation

$$\varphi^m(x) = \frac{a(x)}{\Gamma(\alpha)} \int_0^x \frac{\varphi(t) dt}{(x-t)^{1-\alpha}} + f(x) \quad (0 < x < d \leq \infty) \quad (4.1)$$

with  $\alpha > 0, m \neq 0, -1, -2, \dots$ , provided that  $a(x)$  and  $f(x)$  have the asymptotics

$$a(x) \sim x^{\alpha p m} \sum_{k=-l}^{\infty} a_k x^{\alpha k} \quad (x \rightarrow 0) \quad (4.2)$$

with  $a_{-l} \neq 0$  and

$$f(x) \sim x^{\alpha p m} \sum_{k=-n}^{\infty} f_k x^{\alpha k} \quad (x \rightarrow 0) \quad (4.3)$$



with  $f_{-n} \neq 0$ , where  $p = 0, 1, 2, \dots, l, n \in \mathbb{Z}$ .

First we consider the case  $n = l - p - 1 \geq 0$ . We shall seek an asymptotic solution  $\varphi(x)$  of (4.1) in the form

$$\varphi(x) \sim \sum_{k=p}^{\infty} \varphi_k x^{\alpha k} \quad (x \rightarrow 0). \quad (4.4)$$

Here (4.3) takes the form

$$f(x) \sim x^{\alpha p m} \sum_{k=p+1-l}^{\infty} f_k x^{\alpha k} \quad (x \rightarrow 0). \quad (4.5)$$

with  $p = 0, 1, 2, \dots, f_{p+1-l} \neq 0$

Making the same arguments as in Section 2, we arrive at the asymptotic relation, as  $x \rightarrow 0$ , similar to (3.8):

$$\begin{aligned} x^{\alpha p m} \sum_{k=0}^{\infty} \Phi_{p,k} x^{\alpha k} \sim x^{\alpha p m} \sum_{k=p+1-l}^{\infty} \left( \sum_{i=0}^{k+l-p-1} \frac{a_{k-i-p-1} \Gamma(\alpha[i+p]+1) \varphi_{i+p}}{\Gamma(\alpha[i+p+1]+1)} \right) x^{\alpha k} \\ + x^{\alpha p m} \sum_{k=p+1-l}^{\infty} f_k x^{\alpha k} \quad (x \rightarrow 0), \end{aligned} \quad (4.6)$$

where the coefficients  $\Phi_{p,k}$  are expressed via the coefficients  $\varphi_k$  by (2.2) - (2.3).

If  $l-p-1 \geq 1$ , then we obtain from (4.6) that when the coefficients  $\varphi_k$  satisfy the relations

$$\sum_{i=0}^{k+l-p-1} \frac{a_{k-i-p-1} \Gamma(\alpha[p+i]+1) \varphi_{i+p}}{\Gamma(\alpha[i+p+1]+1)} + f_k = 0 \quad (k = p+1-l, p+2-l, \dots, -1), \quad (4.7)$$

$$\Phi_{p,k} = \sum_{i=0}^{k+l-p-1} \frac{a_{k-i-p-1} \Gamma(\alpha[p+i]+1) \varphi_{i+p}}{\Gamma(\alpha[p+i+1]+1)} + f_k \quad (k = 0, 1, 2, \dots), \quad (4.8)$$

(4.4) is the asymptotic solution of the equation (4.1). If  $l-p-1 = 0$ , then it follows from (4.6) that when the coefficients  $\varphi_k$  satisfy the relations

$$\Phi_{p,k} = \sum_{i=0}^k \frac{a_{k-i-p-1} \Gamma(\alpha[p+i]+1) \varphi_{i+p}}{\Gamma(\alpha[p+i+1]+1)} + f_k \quad (k = 0, 1, 2, \dots), \quad (4.9)$$

(4.4) is also the asymptotic solution of the equation (4.1).

Consequently we obtain the following result.

**Theorem 3.** Let  $p = 0, 1, 2, \dots$  and  $l$  be an integer such that  $l \geq p+1$  and let the functions  $a(x)$  and  $f(x)$  have the asymptotic expansions (4.2) and (4.5) with  $n = l - p - 1$ . Let the coefficients  $\varphi_k$  satisfy the relations (4.7) and (4.8) if  $l > p+1$  and the relation (4.9) if  $l = p+1$ . Then the integral equation (4.1) is asymptotically solvable in the space of locally bounded functions on  $(0, d)$  with  $0 < d \leq \infty$ , and its asymptotic solution  $\varphi(x)$  has the form (4.4).

Now we consider the case  $n < l - p - 1$ . We shall seek an asymptotic solution  $\varphi(x)$  of (4.1) in the form

$$\varphi(x) \sim \sum_{k=l-n-1}^{\infty} \varphi_k x^{\alpha k} \quad (x \rightarrow 0). \quad (4.10)$$

and come to the asymptotic relation

$$\begin{aligned} x^{\alpha(l-n-1)m} \sum_{k=0}^{\infty} \Phi_{l-n-1,k} x^{\alpha k} &\sim x^{\alpha p m} \sum_{k=-n}^{\infty} \left( \sum_{i=l-n-p-1}^{k+l-p-1} \frac{a_{k-i-p-1} \Gamma(\alpha[i+p]+1) \varphi_{i+p}}{\Gamma(\alpha[i+p+1]+1)} \right) x^{\alpha k} \\ &+ x^{\alpha p m} \sum_{k=-n}^{\infty} f_k x^{\alpha k} \quad (x \rightarrow 0), \end{aligned} \quad (4.11)$$

where  $\Phi_{l-n-1,k}$  are expressed via  $\varphi_k$  by (2.2) - (2.3).

Let now suppose that  $q = (l - n - p - 1)m$  be an integer for  $m \neq 0, -1, -2, \dots$  such that  $q \geq -n$ . Then (4.11) is equivalent to the relation

$$\begin{aligned} x^{\alpha p m} \sum_{k=q}^{\infty} \Phi_{l-n-1,k-q} x^{\alpha k} &\sim x^{\alpha p m} \sum_{k=-n}^{\infty} \left( \sum_{i=l-n-p-1}^{k+l-p-1} \frac{a_{k-i-p-1} \Gamma(\alpha[i+p]+1) \varphi_{i+p}}{\Gamma(\alpha[i+p+1]+1)} \right) x^{\alpha k} \\ &+ x^{\alpha p m} \sum_{k=-n}^{\infty} f_k x^{\alpha k} \quad (x \rightarrow 0), \end{aligned} \quad (4.12)$$

from which we obtain that when  $q > -n$  and the coefficients  $\varphi_k$  satisfy the equalities

$$\sum_{i=l-n-p-1}^{k+l-p-1} \frac{a_{k-i-p-1} \Gamma(\alpha[i+p]+1) \varphi_{i+p}}{\Gamma(\alpha[i+p+1]+1)} + f_k = 0 \quad (k = -n, -n+1, \dots, q-1), \quad (4.13)$$

$$\Phi_{l-n-1,k-q} = \sum_{i=l-n-p-1}^{k+l-p-1} \frac{a_{k-i-p-1} \Gamma(\alpha[i+p]+1) \varphi_{i+p}}{\Gamma(\alpha[i+p+1]+1)} + f_k \quad (k = q, q+1, \dots), \quad (4.14)$$

(4.10) is the asymptotic solution of the equation (4.1). If  $q = -n$ , then it follows from (4.12) that when the coefficients  $\varphi_k$  satisfy the relation (4.14), (4.10) is also the asymptotic solution of the equation (4.1).

Hence we arrive at the following statement.

**Theorem 4.** Let  $p = 0, 1, 2, \dots$  and  $l, n$  be integers with  $l - p - 1 > n$  and let  $q = (l - n - p - 1)m$  be an integer for  $m \neq 0, -1, -2, \dots$  such that  $q \geq -n$ . Let the functions  $a(x)$  and  $f(x)$  have the asymptotic expansions (4.2) and (4.3) and let the coefficients  $\varphi_k$  satisfy the relations (4.13) and (4.14) if  $q > -n$  and the relation (4.14) if  $q = -n$ . Then the integral equation (4.1) is asymptotically solvable in the space of locally bounded functions on  $(0, d)$  with  $0 < d \leq \infty$ , and its asymptotic solution  $\varphi(x)$  has the form (4.10).

## 5. Asymptotic Solutions of Nonlinear Equations in More General Case

The results obtained in Sections 2 and 3 allow us to find the asymptotic behavior of the solutions  $\varphi(x)$  of the nonlinear integral equations (1.5), as  $x \rightarrow 0$ , provided that  $a(x)$  and  $f(x)$  have the asymptotic expansions (1.6) and (1.7) under additional assumptions on numbers  $m, l, n$  and  $p = -1, 0, 1, \dots$ , when  $l - p - 1 = n \geq 0$  and when  $l - p - 1 > n$  and  $q = (l - n - p - 1)m$ , ( $m \neq 0, -1, -2, \dots$ ) is an integer such that  $q \geq -n$ . The case  $p = -1$  was considered in Theorems 1 and 2 and  $p = 0, 1, 2, \dots$  in Theorems 3 and 4. They were caused by our investigations based on the asymptotic relations (3.8), (3.15), (4.6) and (4.12). Such an approach can be applied in some other cases, however the results will be more complicated.

In the present section we illustrate this fact for the nonlinear integral equation (1.5):

$$\varphi^m(x) = \frac{a(x)}{\Gamma(\alpha)} \int_0^x \frac{\varphi(t) dt}{(x-t)^{1-\alpha}} + f(x) \quad (0 < x < d \leq \infty) \quad (5.1)$$

with  $\alpha > 0, m \neq 1, 0, -1, -2, \dots$  in the case when  $a(x)$  and  $f(x)$  have the asymptotics (1.6) and (1.7) with  $n = l - p - 1 < 0, p = -1, 0, 1, \dots, l \in \mathbb{Z}$ :

$$a(x) \sim x^{\alpha p m} \sum_{k=-l}^{\infty} a_k x^{\alpha k} \quad (x \rightarrow 0) \quad (5.2)$$

with  $a_{-l} \neq 0$ , and

$$f(x) \sim x^{\alpha p m} \sum_{k=p-l+1}^{\infty} f_k x^{\alpha k} \quad (x \rightarrow 0) \quad (5.3)$$

with  $f_{p-l+1} \neq 0$ . The equation (5.1) does not belong to the equations described by Theorems 1 and 3 because  $n = l - p - 1 < 0$ .

We shall seek an asymptotic solution  $\varphi(x)$  of the equation (5.1) in the form

$$\varphi(x) \sim \sum_{k=q}^{\infty} \varphi_k x^{\alpha k} \quad (x \rightarrow 0), \quad (5.4)$$

where  $q$  is an unknown integer. If we suppose that  $m(q - p)$  is an integer, then applying the same arguments as in Theorems 1 and 3, we come to the asymptotic relation

$$\begin{aligned} & x^{\alpha p m} \sum_{k=m(q-p)}^{\infty} \Phi_{q,k-m(q-p)} x^{\alpha k} \\ & \sim x^{\alpha p m} \sum_{k=q-l+1}^{\infty} \left( \sum_{i=0}^{k+l-q-1} \frac{a_{k-i-q-1} \Gamma(\alpha[i+q]+1) \varphi_{i+q}}{\Gamma(\alpha[i+q+1]+1)} \right) x^{\alpha k} \\ & + x^{\alpha p m} \sum_{k=p-l+1}^{\infty} x^{\alpha k} f_k \quad (x \rightarrow 0). \end{aligned} \quad (5.5)$$

If we suppose that  $m > 0$  and  $(p - l + 1)/m$  is an integer and take  $q$  as

$$q = p + \frac{p - l + 1}{m}, \quad (5.6)$$

then  $m(q-p) = p-l+1 > 0$  is a positive integer, and  $q > p$  and  $q \geq 0$ . Hence from (5.5) we obtain that if the coefficients  $\varphi_k$  satisfy the equalities

$$\Phi_{q,k+l-p-1} = f_k \quad (k = p-l+1, p-l, \dots, q-l), \quad (5.7)$$

$$\Phi_{q,k+l-p-1} = \sum_{i=0}^{k+l-q-1} \frac{a_{k-i-q-1} \Gamma(\alpha[i+q]+1) \varphi_{i+q}}{\Gamma(\alpha[i+q+1]+1)} + f_k \quad (k = q-l+1, q-l+2, \dots), \quad (5.8)$$

then the equation (5.1) is asymptotically solvable in the space of locally bounded functions on  $(0, \infty)$  and its asymptotic solution has the form (5.4).

Thus we obtain the following result.

**Theorem 5.** Let  $m > 0$ ,  $p = -1, 0, 1, \dots, l$  be an integer such that  $p-l+1 > 0$  and  $(p-l+1)/m$  is integer and let  $q = p + (p-l+1)/m$ . Let  $a(x)$  and  $f(x)$  have the asymptotic expansions (5.2) and (5.3). If the coefficients  $\varphi_k$  satisfy the relations (5.7) and (5.8), then the equation (5.1) is asymptotically solvable in the space of locally bounded functions on  $(0, d)$  with  $0 < d \leq \infty$ , and its asymptotic solution  $\varphi(x)$  has the form (5.4).

Letting  $p = -1$ , and  $l$  be  $-l$  in Theorem 5, we have

**Corollary 5.1.** Let  $m > 0$  and  $l$  be a positive integer such that  $l/m$  is an integer and set  $q = -1 + l/m$ . Let  $l = 1, 2, \dots$

$$a(x) \sim x^{-\alpha m} \sum_{k=l}^{\infty} a_k x^{\alpha k} \quad (x \rightarrow 0) \quad (5.9)$$

with  $a_l \neq 0$ , and

$$f(x) \sim x^{-\alpha m} \sum_{k=l}^{\infty} f_k x^{\alpha k} \quad (x \rightarrow 0) \quad (5.10)$$

with  $f_l \neq 0$ , and let the coefficients  $\varphi_k$  satisfy the relations

$$\Phi_{q,k-l} = f_k \quad (k = l, l+1, \dots, l+q), \quad (5.11)$$

$$\Phi_{q,k-l} = \sum_{i=0}^{k-l-q-1} \frac{a_{k-i-q-1} \Gamma(\alpha[i+q]+1) \varphi_{i+q}}{\Gamma(\alpha[i+q+1]+1)} + f_k \quad (k = q+l+1, q+l+2, \dots). \quad (5.12)$$

Then the equation (5.1) is asymptotically solvable in the space of locally bounded functions on  $(0, d)$  with  $0 < d \leq \infty$ , and its asymptotic solution  $\varphi(x)$  has the form (5.4).

If we suppose that  $m < 1$  and  $(p-l+1)/(1-m)$  is an integer and take  $q$  as

$$q = p - \frac{p-l+1}{1-m}, \quad (5.13)$$

then  $m(q-p) = q-l+1$  is a negative integer and  $q < p$ . Hence from (5.5) we obtain that if the coefficients  $\varphi_k$  satisfy the equalities

$$\Phi_{q,k+l-q-1} = \sum_{i=0}^{k+l-q-1} \frac{a_{k-i-q-1} \Gamma(\alpha[i+q]+1) \varphi_{i+q}}{\Gamma(\alpha[i+q+1]+1)} \quad (5.14)$$

$$(k = q-l+1, q-l+2, \dots, p-l),$$

$$\Phi_{q,k+l-q-1} = \sum_{i=0}^{k+l-q-1} \frac{a_{k-i-q-1} \Gamma(\alpha[i+q]+1) \varphi_{i+q}}{\Gamma(\alpha[i+q+1]+1)} + f_k \quad (5.15)$$

$$(k = p-l+1, p-l+2, \dots),$$

then (5.4) is also the asymptotic solution of the equation (5.1). When  $p = 0, 1, 2, \dots$  and  $m = l/(p+1)$ , then  $q = -1$  and (5.4) is the locally integrable solution on  $(0, \infty)$ . When  $p = 1, 2, \dots$  and  $pm \leq l-1$  then  $q \geq 0$  and (5.4) is the locally bounded solution on  $(0, \infty)$ .

Therefore we arrive at the following result.

**Theorem 6.** Let  $m < 1, p = 0, 1, 2, \dots, l$  be a integer such that  $(p+1-l)/(1-m)$  is integer and let  $q = p - (p-l+1)/(1-m)$ . If  $m = l/(p+1)$  and the coefficients  $\varphi_k$  satisfy the relations (5.14) and (5.15), then the equation (5.1) is asymptotically solvable in the space of locally integrable functions on  $(0, d)$  with  $0 < d \leq \infty$ , and its asymptotic solution has the form (5.4) with  $q = -1$ . If  $p = 1, 2, \dots, pm \leq l-1$  and  $\varphi_k$  satisfy the relations (5.14) and (5.15), then the equation (5.1) is asymptotically solvable in the space of locally bounded functions on  $(0, d)$  with  $0 < d \leq \infty$ , and its asymptotic solution  $\varphi(x)$  has the form (5.4).

**Remark 1.** In Sections 3 - 5 we found the power asymptotic solutions (1.8) of the equation (1.5) in the spaces of locally integrable and locally bounded functions on  $(0, d)$  with  $0 < d \leq \infty$ . However, the existence of the solution  $\varphi(x)$  itself of the integral equation (1.5) does not follow from the existence of its asymptotic solution.

## 6. Asymptotic Solution of Nonlinear Equations with Integral Exponent Nonlinearity

In this section we pick out the asymptotic solutions  $\varphi(x)$  of the equations (1.5) with the integer  $m = 2, 3, \dots$  which are met in applications [8], [17], [19]. First we consider this equation in the case  $0 < \alpha < 1$ :

$$\varphi^m(x) = \frac{a(x)}{\Gamma(\alpha)} \int_0^x \frac{\varphi(t) dt}{(x-t)^{1-\alpha}} + f(x) \quad (0 < x < d \leq \infty), \quad (6.1)$$

provided that  $a(x)$  and  $f(x)$  have the asymptotics (3.2) and (3.3). We note that when  $l > n$ ,  $q = (l-n)m$  is an integer and, if additionally  $n \geq -m$ , the condition  $q \geq -n$  is satisfied. Therefore from Theorems 1 and 2 and Lemma 2 we obtain the following assertion.

**Theorem 7.** Let  $m = 2, 3, \dots, l$  and  $n$  be integers with  $n \leq l$  such that  $n \geq 0$  if  $l = n$  and  $n \geq -m$  if  $l > n$ . Let  $a(x)$  and  $f(x)$  have the asymptotic expansions (3.2) and (3.3). Let the coefficients  $\varphi_k$  satisfy the relations

$$\sum_{i=l-n}^{k+l} \frac{a_{k-i} \Gamma(\alpha i - \alpha + 1) \varphi_{i-1}}{\Gamma(\alpha i + 1)} + f_k = 0 \quad (k = -n, -n+1, \dots, (l-n)m-1), \quad (6.2)$$

$$\Phi_{l-n-1, k-(l-n)m} = \sum_{i=l-n}^{k+l} \frac{a_{k-i} \Gamma(\alpha i - \alpha + 1) \varphi_{i-1}}{\Gamma(\alpha i + 1)} + f_k \quad (k = (l-n)m, (l-n)m+1, \dots), \quad (6.3)$$

if  $(l-n)m+n > 0$  and the relation (6.3) if  $(l-n)m+n = 0$ . Then the nonlinear integral equation (6.1) is asymptotically solvable in the space of locally integrable functions on  $(0, d)$  with  $0 < d \leq \infty$  when  $l = n$  and in the space of locally bounded functions on  $(0, d)$  with  $0 < d \leq \infty$ , when  $l > n$ . Its asymptotic solution  $\varphi(x)$  has the form

$$\varphi(x) \sim \sum_{k=l-n-1}^{\infty} \varphi_k x^{\alpha k} \quad (x \rightarrow 0). \quad (6.4)$$

Now we consider the equation in the case  $\alpha > 0$ :

$$\varphi^m(x) = \frac{a(x)}{\Gamma(\alpha)} \int_0^x \frac{\varphi(t) dt}{(x-t)^{1-\alpha}} + f(x) \quad (0 < x < d \leq \infty) \quad (6.5)$$

with  $m = 2, 3, \dots$ , provided that  $a(x)$  and  $f(x)$  have the asymptotics (4.2) and (4.3). As earlier we see that if  $l-p-1 > n$ , then  $q = (l-n-p-1)m$  is an integer and if additionally  $n \geq -m$ , then the condition  $q \geq -n$  is satisfied. Therefore from Theorems 3 and 4 and Lemma 2 we obtain the statement similar to Theorem 7.

**Theorem 8.** Let  $m = 2, 3, \dots, p = 0, 1, 2, \dots, l$  and  $n$  be integers with  $n \leq l-p-1$  such that  $n \geq 0$  when  $l-p-1 = n$  and  $n \geq -m$  when  $l-p-1 > n$ . Let  $a(x)$  and  $f(x)$  have the asymptotic expansions (4.2) and (4.3). Let the coefficients  $\varphi_k$  satisfy the relations

$$\sum_{i=l-n-p-1}^{k+l-p-1} \frac{a_{k-i-p-1} \Gamma(\alpha[i+p]+1) \varphi_{i+p}}{\Gamma(\alpha[i+p+1]+1)} + f_k = 0 \quad (6.6)$$

$$(k = -n, -n+1, \dots, (l-n-p-1)m-1),$$

$$\Phi_{l-n-1, k-(l-n-p-1)m} = \sum_{i=l-n-p-1}^{k+l-p-1} \frac{a_{k-i-p-1} \Gamma(\alpha[i+p]+1) \varphi_{i+p}}{\Gamma(\alpha[i+p+1]+1)} + f_k \quad (6.7)$$

$$(k = (l-n-p-1)m, (l-n-p-1)m+1, \dots),$$

if  $(l-n-p-1)m+n > 0$  and the relation (6.7) if  $(l-n-p-1)m+n = 0$ . Then the nonlinear integral equation (6.5) is asymptotically solvable in the space of locally bounded functions on  $(0, d)$  with  $0 < d \leq \infty$ , and its asymptotic solution  $\varphi(x)$  has the form (6.4).

The statements of Theorem 5 and Corollary 5.1 are also valid for the integral equation (6.5).

**Theorem 9.** Let  $m = 2, 3, \dots$ ,  $p = -1, 0, 1, \dots$  and  $l$  be an integer such that  $(p+1-l)/m$  is a positive integer and let  $q = p + (p+1-l)/m$ . Let  $a(x)$  and  $f(x)$  have the asymptotic expansions (5.2) and (5.3) and let the coefficients  $\varphi_k$  satisfy the relations (5.7) and (5.8). Then the equation (6.5) is asymptotically solvable in the space of locally bounded functions on  $(0, d)$  with  $0 < d \leq \infty$ , and its asymptotic solution  $\varphi(x)$  has the form

$$\varphi(x) \sim \sum_{k=q}^{\infty} \varphi_k x^{\alpha_k} \quad (x \rightarrow 0). \quad (6.8)$$

**Corollary 9.1.** Let  $m = 2, 3, \dots$  and  $l$  be a positive integer such that  $l/m$  is an integer and  $q = -1 + l/m$ . Let  $a(x)$  and  $f(x)$  have the asymptotic expansions (5.9) and (5.10) and let the coefficients  $\varphi_k$  satisfy the relations (5.11) - (5.12). Then the equation (6.5) is asymptotically solvable in the space of locally bounded functions on  $(0, d)$  with  $0 < d \leq \infty$ , and its asymptotic solution  $\varphi(x)$  has the form (6.8).

We also note a useful result which follows from Corollary 9.1 if we take  $l = m = 2, 3, \dots$ .

**Theorem 10.** Let  $m = 2, 3, \dots$  and

$$a(x) \sim \sum_{k=0}^{\infty} a_k x^{\alpha_k} \quad (x \rightarrow 0) \quad (6.9)$$

with  $a_0 \neq 0$  and

$$f(x) \sim \sum_{k=0}^{\infty} f_k x^{\alpha_k} \quad (x \rightarrow 0) \quad (6.10)$$

with  $f_0 \neq 0$ , and let the coefficients  $\varphi_k$  satisfy the relations

$$\Phi_{0,0} = f_0, \quad \Phi_{0,k} = \sum_{i=0}^{k-1} \frac{a_{k-i-1} \Gamma(\alpha_i + 1) \varphi_i}{\Gamma(\alpha_i + \alpha + 1)} + f_k \quad (k = 1, 2, \dots). \quad (6.11)$$

Then the equation (6.5) is asymptotically solvable in the space of locally bounded functions on  $(0, d)$  with  $0 < d \leq \infty$ , and its asymptotic solution  $\varphi(x)$  has the form

$$\varphi(x) \sim \sum_{k=0}^{\infty} \varphi_k x^{\alpha_k} \quad (x \rightarrow 0). \quad (6.12)$$

## 7. Asymptotic Solution of Linear Equation

Let us now discuss the asymptotic behavior of the solution  $\varphi(x)$  of the linear equation (1.9), as  $x \rightarrow 0$ . First we consider this equation in the case  $0 < \alpha < 1$ :

$$\varphi(x) = \frac{a(x)}{\Gamma(\alpha)} \int_0^x \frac{\varphi(t) dt}{(x-t)^{1-\alpha}} + f(x) \quad (0 < x < d \leq \infty), \quad (7.1)$$

provided that  $a(x)$  and  $f(x)$  have the asymptotic expansions

$$a(x) \sim x^{-\alpha} \sum_{k=-l}^{\infty} a_k x^{\alpha k} \quad (x \rightarrow 0) \quad (7.2)$$

with  $l \in \mathbb{Z}$ ,  $a_{-l} \neq 0$ , and

$$f(x) \sim x^{-\alpha} \sum_{k=-n}^{\infty} f_k x^{\alpha k} \quad (x \rightarrow 0) \quad (7.3)$$

with  $n \in \mathbb{Z}$ ,  $f_{-n} \neq 0$ , respectively. In this case the asymptotic relation (3.14) is simplified:

$$\begin{aligned} x^{-\alpha} \sum_{k=l-n}^{\infty} \varphi_{k-1} x^{\alpha k} &\sim x^{-\alpha} \sum_{k=-n}^{\infty} \left( \sum_{i=l-n}^{k+l} \frac{a_{k-i} \Gamma(\alpha i - \alpha + 1) \varphi_{i-1}}{\Gamma(\alpha i + 1)} \right) x^{\alpha k} \\ &+ x^{-\alpha} \sum_{k=-n}^{\infty} f_k x^{\alpha k} \quad (x \rightarrow 0). \end{aligned} \quad (7.4)$$

We thus obtain the following assertions:

a) If  $l \geq 0$  and  $l \geq n$  and the coefficients  $\varphi_k$  satisfy the relations

$$\sum_{i=l-n}^{k+l} \frac{a_{k-i} \Gamma(\alpha i - \alpha + 1) \varphi_{i-1}}{\Gamma(\alpha i + 1)} + f_k = 0 \quad (k = -n, -n+1, \dots, l-n-1), \quad (7.5)$$

$$\varphi_{k-1} = \sum_{i=l-n}^{k+l} \frac{a_{k-i} \Gamma(\alpha i - \alpha + 1) \varphi_{i-1}}{\Gamma(\alpha i + 1)} + f_k \quad (k = l-n, l-n+1, \dots), \quad (7.6)$$

when  $l > 0$  and (7.6) when  $l = 0$ , then the asymptotic solution  $\varphi(x)$  of the equation (7.1) has the form

$$\varphi(x) \sim \sum_{k=l-n-1}^{\infty} \varphi_k x^{\alpha k} \quad (x \rightarrow 0). \quad (7.7)$$

b) If  $0 > l \geq n$  and the coefficients  $\varphi_k$  satisfy the relations

$$\varphi_{k-1} = f_k \quad (k = -n, -n+1, \dots, -n-l-1), \quad (7.8)$$

$$\varphi_{k-1} = \sum_{i=-n}^{l+k} \frac{a_{k-i} \Gamma(\alpha i - \alpha + 1) \varphi_{i-1}}{\Gamma(\alpha i + 1)} + f_k \quad (k = -n-l, -n-l+1, -n-l+2, \dots), \quad (7.9)$$



then the asymptotic solution  $\varphi(x)$  of the equation (7.1) has the form

$$\varphi(x) \sim \sum_{k=-n-1}^{\infty} \varphi_k x^{\alpha k} \quad (x \rightarrow 0). \quad (7.10)$$

Therefore we arrive at the following statement.

**Theorem 11.** Let  $n$  and  $l$  be integers such that  $l \geq n$  and let  $a(x)$  and  $f(x)$  have the asymptotic expansions (7.2) and (7.3).

a) Let  $l \geq 0$  and  $l \geq n$  and the coefficients  $\varphi_k$  satisfy the relations (7.5) and (7.6) when  $l > 0$  and the relation (7.6) when  $l = 0$ . Then the linear integral equation (7.1) is asymptotically solvable in the space of locally integrable functions on  $(0, d)$  with  $0 < d \leq \infty$  when  $l = n$  and in the space of locally bounded functions on  $(0, d)$  with  $0 < d \leq \infty$  when  $l > n$ , and its asymptotic solution  $\varphi(x)$  has the form (7.7).

b) Let  $0 > l \geq n$  and the coefficients  $\varphi_k$  satisfy the relations (7.8) and (7.9). Then the linear integral equation (7.1) is asymptotically solvable in the space of functions locally bounded on  $(0, d)$  with  $0 < d \leq \infty$ , and its asymptotic solution  $\varphi(x)$  has the form (7.10).

**Corollary 11.1.** Let  $0 < \alpha < 1$ ,  $a(x)$  and  $f(x)$  have the asymptotic expansions

$$a(x) \sim x^{-\alpha} \sum_{k=0}^{\infty} a_k x^{\alpha k} \quad (x \rightarrow 0) \quad (7.11)$$

with  $a_0 \neq 0$ , and

$$f(x) \sim x^{-\alpha} \sum_{k=0}^{\infty} f_k x^{\alpha k} \quad (x \rightarrow 0) \quad (7.12)$$

with  $f_0 \neq 0$  and let

$$\Gamma(\alpha k - \alpha + 1)a_0 \neq \Gamma(\alpha k + 1) \quad (k = 0, 1, 2, \dots). \quad (7.13)$$

Then the linear integral equation (7.1) is asymptotically solvable in the space of locally integrable functions on  $(0, d)$  with  $0 < d \leq \infty$ , and its asymptotic solution  $\varphi(x)$  has the form

$$\varphi(x) \sim \sum_{k=-1}^{\infty} \varphi_k x^{\alpha k} \quad (x \rightarrow 0), \quad (7.14)$$

where the coefficients  $\varphi_k$  are given by the recurrent equalities

$$\varphi_{-1} = [1 - a_0 \Gamma(1 - \alpha)]^{-1} f_0,$$

$$\varphi_k = \left(1 - \frac{\Gamma(\alpha k + 1)a_0}{\Gamma(\alpha k + \alpha + 1)}\right)^{-1} \left(\sum_{i=0}^k \frac{a_{k+1-i} \Gamma(\alpha i - \alpha + 1) \varphi_{i-1}}{\Gamma(\alpha i + 1)} + f_{k+1}\right) \quad (7.15)$$

$$(k = 0, 1, 2, \dots).$$

**Corollary 11.2.** Let  $a(x)$  and  $f(x)$  have the asymptotic expansions (7.11) and (7.12), respectively. Let there exists an integer  $j \in \{0, 1, 2, \dots\}$  such that

$$\Gamma(\alpha j - \alpha + 1)a_0 = \Gamma(\alpha j + 1). \quad (7.16)$$

Let the coefficients  $f_k$  ( $k = 0, 1, \dots, j$ ) in (7.12) satisfy the relations

$$f_0 = 0 \text{ when } j = 0 \quad \sum_{i=0}^{j-1} \frac{a_{j-i}\Gamma(\alpha i - \alpha + 1)\varphi_{i-1}}{\Gamma(\alpha i + 1)} + f_j = 0 \text{ when } j = 1, 2, \dots, \quad (7.17)$$

where  $\varphi_{i-1}$  ( $i = 0, 1, \dots, j-1$ ) are expressed via  $f_i$  ( $i = 0, 1, \dots, j-1$ ) by means of (7.15). Then the equation (7.1) is asymptotically solvable in the space of locally integrable function on  $(0, d)$  with  $0 < d \leq \infty$  and its solution  $\varphi(x)$  is given by the formula

$$\varphi(x) \sim cx^{\alpha j} + \sum_{k=-1, k \neq j}^{\infty} \varphi_k x^{\alpha k} \quad (x \rightarrow 0). \quad (7.18)$$

Here  $c$  is an arbitrary constant and  $\varphi_k$  for  $k \neq j$  are found from the recurrent relations (7.15). If the conditions (7.17) are not satisfied, the equation (7.1) does not have any asymptotic solution of the form (7.14).

**Remark 2.** Corollaries 11.1 and 11.2 coincide with Theorems 2.1 and 2.2 in [16].

Now we consider the equation (1.9) in the case  $\alpha > 0$ :

$$\varphi(x) = \frac{a(x)}{\Gamma(\alpha)} \int_0^x \frac{\varphi(t)dt}{(x-t)^{1-\alpha}} + f(x) \quad (0 < x < d \leq \infty), \quad (7.19)$$

provided that  $a(x)$  and  $f(x)$  have the asymptotic expansions

$$a(x) \sim x^{\alpha p} \sum_{k=-l}^{\infty} a_k x^{\alpha k} \quad (x \rightarrow 0) \quad (7.20)$$

with  $a_{-l} \neq 0$ , and

$$f(x) \sim x^{\alpha p} \sum_{k=-n}^{\infty} f_k x^{\alpha k} \quad (x \rightarrow 0) \quad (7.21)$$

with  $f_{-n} \neq 0$ , where  $p = 0, 1, 2, \dots, l, n \in \mathbb{Z}$ . The asymptotic relation (4.11) is simplified:

$$\begin{aligned} & x^{\alpha p} \sum_{k=l-n-p-1}^{\infty} \varphi_{k+p} x^{\alpha k} \\ & \sim x^{\alpha p} \sum_{k=-n}^{\infty} \left( \sum_{i=l-n-p-1}^{k+l-p-1} \frac{a_{k-i-p-1}\Gamma(\alpha[i+p]+1)\varphi_{i+p}}{\Gamma(\alpha[i+p+1]+1)} \right) x^{\alpha k} \\ & + x^{\alpha p} \sum_{k=-n}^{\infty} f_k x^{\alpha k}. \end{aligned} \quad (7.22)$$

Thus we obtain the following assertions:

c) If  $l - p - 1 \geq 0$  and  $l - p - 1 \geq n$  and the coefficients  $\varphi_k$  satisfy the relations

$$\sum_{i=l-n-p-1}^{k+l-p-1} \frac{a_{k-i-p-1} \Gamma(\alpha[i+p]+1) \varphi_{i+p}}{\Gamma(\alpha[i+p+1]+1)} + f_k = 0 \quad (7.23)$$

$$(k = -n, -n+1, \dots, l-n-p-2),$$

$$\varphi_{k+p} = \sum_{i=l-n-p-1}^{k+l-p-1} \frac{a_{k-i-p-1} \Gamma(\alpha[i+p]+1) \varphi_{i+p}}{\Gamma(\alpha[i+p+1]+1)} + f_k \quad (7.24)$$

$$(k = l-n-p-1, l-n-p, \dots),$$

when  $l - p - 1 > 0$ , and (7.24) when  $l - p - 1 = 0$ , then the asymptotic solution  $\varphi(x)$  of the equation (7.19) has the form (7.7).

d) If  $0 > l - p - 1 \geq n$  and the coefficients  $\varphi_k$  satisfy the relations

$$\varphi_{k+p} = f_k \quad (k = -n, -n+1, \dots, p-n-l), \quad (7.25)$$

$$\varphi_{k+p} = \sum_{i=-n}^{k+l-p-1} \frac{a_{k-i-p-1} \Gamma(\alpha[i+p]+1) \varphi_{i+p}}{\Gamma(\alpha[i+p+1]+1)} + f_k \quad (7.26)$$

$$(k = p-n-l+1, p-n-l+2, \dots),$$

then the asymptotic solution  $\varphi(x)$  of the equation (7.19) has the form

$$\varphi(x) \sim \sum_{k=p-n}^{\infty} \varphi_k x^{\alpha k} \quad (x \rightarrow 0). \quad (7.27)$$

Therefore we arrive at the following statement.

**Theorem 12.** Let  $p = 0, 1, 2, \dots$  and  $l$  and  $n$  be integers such that  $l - p - 1 \geq n$  and let  $a(x)$  and  $f(x)$  have the asymptotic expansions (7.20) and (7.21).

c) Let  $l - p - 1 \geq 0$  and  $l - p - 1 \geq n$  and the coefficients  $\varphi_k$  satisfy the relations (7.23) and (7.24) when  $l - p - 1 > 0$  and the relations (7.24) when  $l - p - 1 = 0$ . Then the linear integral equation (7.19) is asymptotically solvable in the space of locally bounded functions on  $(0, d)$  with  $0 < d \leq \infty$ , and its asymptotic solution  $\varphi(x)$  has the form (7.7).

d) Let  $0 > l - p - 1 \geq n$  and the coefficients  $\varphi_k$  satisfy the relations (7.25) and (7.26). Then the linear integral equation (7.19) is asymptotically solvable in the space of locally bounded functions on  $(0, d)$  with  $0 < d \leq \infty$ , and its asymptotic solution  $\varphi(x)$  has the form (7.27).

**Corollary 12.1.** Let  $l = 1, 2, \dots, \alpha > 0$ , and  $a(x)$  and  $f(x)$  have the asymptotic expansions

$$a(x) \sim x^{\alpha(l-1)} \sum_{k=-l}^{\infty} a_k x^{\alpha k} \quad (x \rightarrow 0) \quad (7.28)$$

with  $a_{-l} \neq 0$ , and

$$f(x) \sim x^{\alpha(l-1)} \sum_{k=0}^{\infty} f_k x^{\alpha k} \quad (x \rightarrow 0) \quad (7.29)$$

with  $f_0 \neq 0$  and let

$$\Gamma(\alpha[k+l-1]+1)a_{-l} \neq \Gamma(\alpha[k+l]+1) \quad (k=0,1,2,\dots). \quad (7.30)$$

Then the linear integral equation (7.19) is asymptotically solvable in the space of locally bounded functions on  $(0, d)$  with  $0 < d \leq \infty$ , and its asymptotic solution  $\varphi(x)$  has the form

$$\varphi(x) \sim \sum_{k=l-1}^{\infty} \varphi_k x^{\alpha k} \quad (x \rightarrow 0), \quad (7.31)$$

where the coefficients  $\varphi_k$  are given by the recurrent equalities

$$\begin{aligned} \varphi_{l-1} &= \left(1 - \frac{\Gamma(\alpha[l-1]+1)a_{-l}}{\Gamma(\alpha l+1)}\right)^{-1} f_0, \\ \varphi_{k+l} &= \left(1 - \frac{\Gamma(\alpha[k+l]+1)a_{-l}}{\Gamma(\alpha[k+l+1]+1)}\right)^{-1} \\ &\quad \times \left(\sum_{i=0}^k \frac{a_{k-l-i+1} \Gamma(\alpha[i+l-1]+1) \varphi_{i+l-1}}{\Gamma(\alpha[i+l]+1)} + f_{k+1}\right) \quad (k=0,1,2,\dots). \end{aligned} \quad (7.32)$$

**Corollary 12.2.** Let  $l=1,2,\dots$ , and  $a(x)$  and  $f(x)$  have the asymptotic expansions (7.28) and (7.29). Let there exists an integer  $j \in \{0,1,2,\dots\}$  such that

$$\Gamma(\alpha[j+l-1]+1)a_{-l} = \Gamma(\alpha[j+l]+1). \quad (7.33)$$

Let the coefficients  $f_k$  ( $k=0,1,\dots,j$ ) in (7.29) satisfy the relations

$$f_0 = 0 \text{ when } j=0 \quad \sum_{i=0}^{j-1} \frac{a_{j-l-i} \Gamma(\alpha[i+l-1]+1) \varphi_{i+l-1}}{\Gamma(\alpha[i+l]+1)} + f_j = 0 \text{ when } j=1,2,\dots, \quad (7.34)$$

where  $\varphi_{i+l-1}$  ( $i=0,1,\dots,j-1$ ) are expressed via  $f_i$  ( $i=0,1,\dots,j-1$ ) by means of (7.32). Then the equation (7.19) is asymptotically solvable in the space of locally bounded functions on  $(0, d)$  with  $0 < d \leq \infty$ , and its solution  $\varphi(x)$  is given by the formula

$$\varphi(x) \sim c x^{\alpha j} + \sum_{k=l-1, k \neq j}^{\infty} \varphi_k x^{\alpha k} \quad (x \rightarrow 0). \quad (7.35)$$

Here  $c$  is an arbitrary constant and  $\varphi_k$  for  $k \neq j$  are found from the recurrent relations (7.32). If the conditions (7.34) are not satisfied, then the equation (7.19) does not have any asymptotic solution of the form (7.31).

**Remark 3.** If  $l = 1$  and  $0 < \alpha < 1$ , Corollaries 12.1 and 12.2 coincide with Theorems 3.1 and 3.2 in [16].

**Remark 4.** Theorems 11 and 12 allow us to find the asymptotic solutions  $\varphi(x)$  of the linear integral equations (7.1) and (7.19) provided that  $a(x)$  and  $f(x)$  have the asymptotic expansions (7.2), (7.3) and (7.20), (7.21) when  $l \geq n$  and  $l - p - 1 \geq n$ , respectively. Moreover, unlike the nonlinear integral equations (see Sections 3 - 5), we consider all connections between the parameters  $l, n$  and  $p$ .

**Acknowledgement.** The work was initiated during the first author's visit to Fukuoka University on his sabbatical leave from Byelorussian State University.

## References

- [1] S.N. Askhabov: Integral equations of convolution type with power nonlinearity, *Colloq. Math.* **62**(1991), 49-60.
- [2] S.N. Askhabov and M.A. Betilgireev: Nonlinear convolution type equations, *Seminar Analysis, Operator Equations and Numerical Analysis*, 1989/90, (Karl Weierstrasse Institut für Mathematik, Berlin), 1990, 1-30.
- [3] S.N. Askhabov and M.A. Betilgireev: Nonlinear integral equations of convolution type with almost increasing kernels in cones, *Dif. Equat.* **27**(1991), 234-242.
- [4] S.N. Askhabov, N.K. Karapetyants and A.Ya. Yakubov: A nonlinear equation of convolution type (Russian), *Differentsial'nye Uravneniya* **22**(1986), 1606-1609.
- [5] S.N. Askhabov, N.K. Karapetyants and A.Ya. Yakubov: Integral equations of convolution type with a power nonlinearity and their systems, *Soviet Math. Dokl.* **41**(1990), 323-327.
- [6] P.J. Bushell: On a class of Volterra and Fredholm non-linear integral equations, *Math. Proc. Camb. Phil. Soc.* **79**(1976), 329-335.
- [7] P.J. Bushell and W. Okrasinski, Nonlinear Volterra integral equations and the Apéry identities, *Bull. London. Math. Soc.* **24**(1992), 478-484.
- [8] J. Goncerzewicz, H. Marcinkowska, W. Okrasinski and K. Tabisz: On the perlocation of water from a cylindrical reservoir into the surrounding soil, *Zastosow Mat.* **16**(1978), 249-261.
- [9] R. Gorenflo and A.A. Kilbas: Asymptotic solution of a nonlinear Abel-Volterra integral equation of second kind, Preprint No.A-6/93, Freie Universität Berlin, 1993.

- [10] R. Gorenflo and S. Vessela: *Abel Integral Equations, Analysis and Applications*, Springer Verlag, Berlin, 1991.
- [11] G. Gripenberg: Asymptotic solution of some nonlinear Volterra integral equation, *SIAM J. Math. Anal.* **12**(1981), 595-602.
- [12] G. Gripenberg, S.-O. Londen and O. Staffans: *Volterra Integral and Functional Equations*, Cambridge Univ. Press, Cambridge-London-New York, 1990.
- [13] R.A. Handelsman and W.E. Olmstead: Asymptotic solution to a class of nonlinear Volterra integral equation, *SIAM J. Appl. Math.* **22**(1972), 373-384.
- [14] N.K. Karapetyants, On a class of nonlinear equations of convolution type (Russian), *Sci. Proc. Jubilee Sem. Bound. Value Problems, Minsk*, 1985, 158-161.
- [15] J.J. Keller: Propagation of simple nonlinear waves in gas filled tubes with friction, *Z. Angew. Math. Phys.* **32**(1981), 170-181.
- [16] A.A. Kilbas and M. Saigo: On solution of integral equation of Abel-Volterra type, *Differential and Integral Equations* (in press).
- [17] W. Okrasinski: On the existence and uniqueness of nonnegative solution of a certain nonlinear convolution equation, *Ann. Polon. Math.* **36**(1979), 61-72.
- [18] W. Okrasinski: On a nonlinear convolution equation occurring in the theory of water percolation, *Ann. Polon. Math.* **37**(1980), 223-229.
- [19] W. Okrasinski: Nonlinear Volterra equations and physical applications, *Extracta Math.* **4**(1989), 51-80.
- [20] W.E. Olmstead and R.A. Handelsman: Asymptotic solution to a class of nonlinear Volterra integral equation II, *SIAM J. Appl. Math.* **30**(1976), 180-189.
- [21] S.G. Samko, A.A. Kilbas and O.I. Marichev: *Fractional Integrals and Derivatives. Theory and Applications*, Gordon and Breach, New York-Philadelphia-London-Paris-Montreux-Tokyo-Melbourne, 1993.
- [22] W.R. Schneider: The general solution of a non-linear integral equation of convolution type, *Z. Angew. Math. Phys.* **33**(1982), 140-142.